

# Automation of Hubble Space Telescope Mission Operations

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On June 13, 2011, after more than 21 years, 115 thousand orbits, and nearly 1 million exposures taken, the operation of the Hubble Space Telescope successfully transitioned from 24x7x365 staffing to 8x5 staffing. This required the automation of routine mission operations including telemetry and forward link acquisition, data dumping and solid-state recorder management, stored command loading, and health and safety monitoring of both the observatory and the HST Ground System. These changes were driven by budget reductions, and required ground system and onboard spacecraft enhancements across the entire operations spectrum, from planning and scheduling systems to payload flight software. Changes in personnel and staffing were required in order to adapt to the new roles and responsibilities required in the new automated operations era. This paper will provide a high level overview of the obstacles to automating nominal HST mission operations, both technical and cultural, and how those obstacles were overcome.

## I. Purpose and Goals of Automation

IN late 2006, while preparations for Servicing Mission 4 were underway, out-year budget projections for HST Mission Operations indicated that severe budget-driven staff cuts of approximately 50% would have to occur. An HST Project team was assembled and tasked with producing the most cost-efficient operations concept while maintaining HST's minimum acceptable risk posture and complete science data collection rate. This task included the development of the methodology to assess options for 'best value' (see 7<sup>th</sup> RCSGSO – Operations Modeling for Hubble Space Telescope – M. Prior, et.al.), sensitive to cost savings, efficiency and risk, with identification of key facilities and equipment within HST inventory that should be retained to support on-orbit operations, and examination of upfront costs and investments that would be required. This assessment and the implementation of its recommendations were schedule-driven by the post-Servicing Mission 4 HST Operations contract RFP hard date of October 1, 2010, and the start of that contract on July 1, 2011.

While cost savings, consolidations and efficiencies could be identified, for most HST Operations departments including Systems Management, Systems Engineering, Flight Software, Hubble Integrated Test Team, Ground Systems and Systems Administration, it meant 'make do with less'. This translates to fewer spacecraft flight software and ground system updates, and slower responses or recovery rather than outright elimination of these functions. Significant reduction of the Flight Operations Team consisting of the Observatory operators, ground system operators, and level-zero data processing operators could be accomplished with the introduction of

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significant end-to-end changes to HST operations from Planning & Scheduling to Observatory Flight Software, and staff and systems consolidation (see Figure 1).

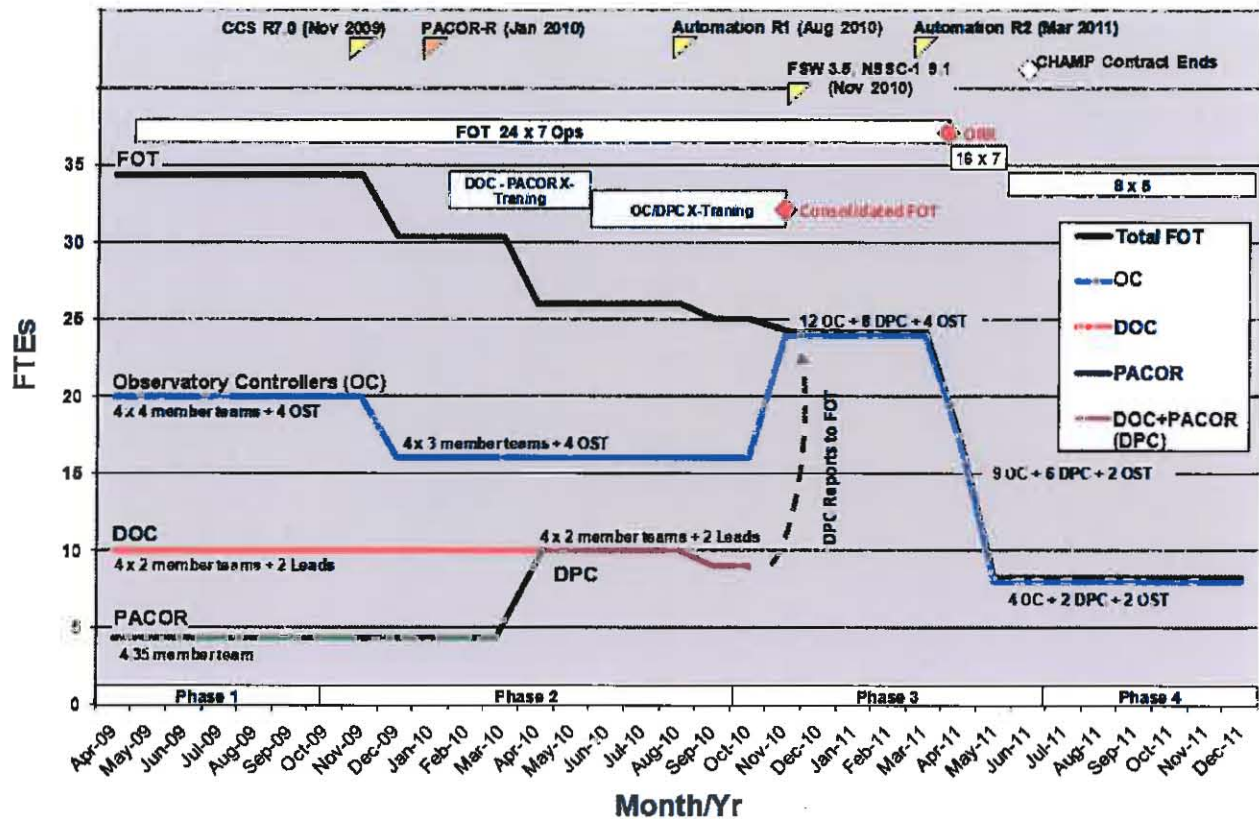


Figure 1. Flight Operations Staff Consolidation Summary – Separate operations teams were co-located, consolidated, cross-trained and were reduced by 75% with automation of routine operations

## II. Introduction to Pre-AO HST Operations

Like most spacecraft, HST operates primarily on stored commands. The Planning and Scheduling (PASS) team at the Space Telescope Science Institute (STScI) nominally delivers command loads weekly; however, re-planning can occur outside this nominal schedule for multiple reasons. Re-planning due to a target of opportunity is a prime example.

The Flight Operations Team (FOT) conducted HST operations on a 24x7 rotating shift schedule. The FOT itself was comprised of four separate sub-teams, on two separate contracts, working in separate facilities, as follows:

- Observatory Controllers (4 per shift) performed all operations on the HST Observatory including telemetry and forward link acquisition, commanding, and health and safety monitoring, from the Space Telescope Operations Control Center (STOCC).
- Data Operations Center (DOC) (two per shift) monitored and maintained configuration of all local ground system elements. Local ground system elements consist of three Operational strings responsible for HST command and control, two science data processing strings and associated user workstations located in two separate facilities. Over 100 separate hardware components were monitored, including all network infrastructure. If a ground system failure occurred, the DOC was visually alerted to the failure and would work the problem, leaving the Observatory Controllers free to continue operations on the HST.
- PACOR Level-0 processing facility was created in 1991, and at one time served 12 missions performing level-0 processing on Time-Division-Multiplexed (TDM) formatted science telemetry, and distributing it to their science data centers, with the STScI being the science data processing and archive site for HST. After 2005, a PACOR system dedicated to HST was provided.



- Operations Support Team (OST) members provided management and training of the other FOT sub-teams, coordinated their activities with the other elements of the HST Project, and represented them at Project meetings.

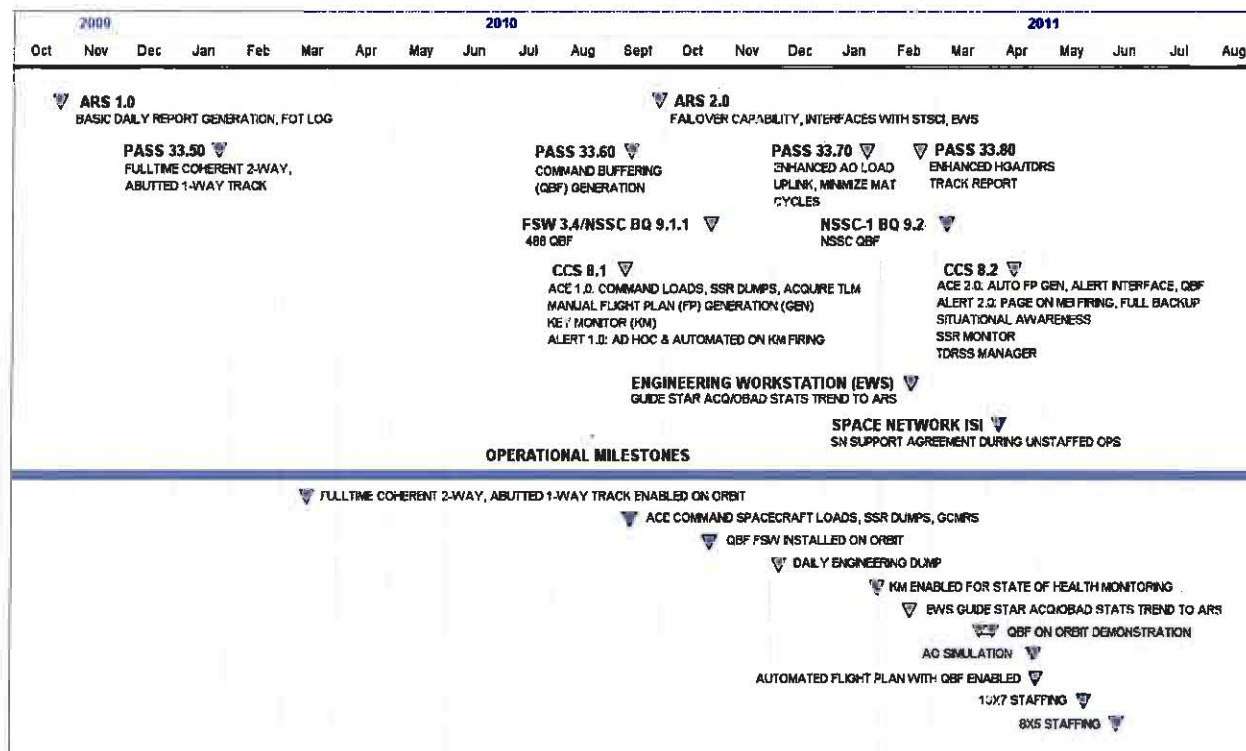
Routine HST operations were conducted and managed by the Observatory Controllers following pre-approved procedures. These procedures guided the controller thru the execution and verification of the multiple steps needed to perform commanding. Any special or contingency commanding requested by HST Systems-Engineers and approved by the NASA and FOT Mission Operations Managers had to be integrated into these routine operations by the Observatory controllers. These special commanding activities included:

- Return and forward link acquisition – HST operations required ~20 to 25 TDRSS passes per day. The nominal TDRSS schedule was part of the weekly PASS product delivery from the STScI. Adjustments to this schedule during the week were common. The impacts of any changes were assessed by the controllers. Usually, these consisted of small service time ‘trims’ and were usually benign and known several days in advance; however, entire passes were sometimes dropped with little warning. These were usually due to problems with TDRSS and higher priority mission supports.
- Solid State Recorder (SSR) dumping and management – Downlink of recorded science data could only be done when TDRS/ S-band Single-Access Return (SSA-R) service was scheduled. In order to minimize the number of cycles placed on the HST SSA transmitters, PASS provided one downlink opportunity for any science observation. Downlink margin occurred because PASS slightly overestimated science data volume, and subsequent loss of SSA-R time or data lost on the downlink and requiring re-dump impacted our ability to recover 100.00% of our science data. The data locations and dump durations were calculated by the observatory controllers and manually commanded.
- Uplink of stored command loads – Stored command loads were uplinked ~four times per day. Typically, three or four uplink windows were scheduled by PASS for each command load, starting on average 3.5 hours before its ‘load-by’ time, in large part due to the limited memory capacity of the HST payload computer. Failure to get a load up in time resulted in safemode entry. TDRS schedule changes such as pass deletions or even the forward link trimmed too short for a load to be completely uplinked had to be closely monitored by the Observatory Controllers.
- Tracking data acquisition – Tracking data was collected ~8 times per day by the Observatory Controllers. During periods where TDRS two-way Doppler tracking service were scheduled, the controllers issued commands to HST and Ground Control Message Requests (GCMRs) to White Sands Complex (WSC) to reconfigure to coherent-mode, from our nominal mode of non-coherent for the collection of this data, then they would reconfigure back to nominal.
- Observatory Health and Safety monitoring – Observatory Controllers monitored spacecraft health and safety real-time telemetry data consisting of more than 3900 limit-checked mnemonics. The evaluation of these mnemonics was complicated by multiple factors, including:
  - Lack of Reed-Solomon engineering data encoding – Out-of-Limits (OOL) conditions occurred during return-link acquisition, transition to and from tracking mode, premature loss of signal (LOS), and during periods of noisy data. Observatory controllers had to remain aware of RF quality at all times, account for these events, and ignore ‘single-sample’ telemetry hits. Evaluation of ‘single-sample’ was complicated by the fact that telemetry sample rates varied by telemetry format.
  - OOL evaluation not automated – Many HST OOL conditions were expected and posed no risk to the observatory. The proper responses by the controllers to these cases were documented in Routine Out-of-Limits (ROOL) documentation. The Observatory Controller responded to anomalous OOL or ground system conditions by performing any restorative commanding, documenting it in an HST Anomaly Report (HSTAR), and communicating with on-call systems engineers when necessary. Some examples of ROOL included:
    - Reaction Wheel Torque for multiple samples during a vehicle slew
    - Total commanded torque while in the South Atlantic Anomaly (SAA) due to its weak magnetic field
    - Gyro analog rates and saturation error counts for multiple samples when switching the gyros between high and low modes
  - Guide Star Acquisition monitoring not automated – Guide-Star acquisitions were monitored and recorded by the Observatory Controllers. Acquisitions failed for a multitude of reasons (binary stars were the most common reason). Multiple consecutive failures resulted in the inability to perform on-board gyro bias updates and an accumulated attitude error that potentially required ground intervention by Observatory Controllers and System Engineers.



experience was followed. In addition to the well-known benefits of this standard development model, it assured HST Project and upper management buy-in.

- Development compensated for a hard schedule end-date associated with the end of the existing contract.
- Risks were mitigated by using multiple releases (see Figure 3). The most challenging aspects of the automation were execution of all routine commanding during TDRSS passes, and reliable health & safety monitoring. Delivering these capabilities within the initial releases allowed for an eight month long period of 'shadow-mode' where the FOT was still in place 24x7 monitoring both the Observatory and the automation and able to rapidly resume manual control if necessary. This long operational verification period allowed problems to be identified for correction in the final release, allowed time for the health and safety rules to be refined, and perhaps most importantly, time for the HST team to gain confidence in the system.
- No changes to the ground software development process were made. The HST ground system team software development process had an established record of producing highly reliable software and meeting all schedule commitments. It was deemed by the HST team that attempting to change or accelerate its process would represent a greater overall risk to success than would be gained in schedule.
- Changes were introduced incrementally. Changes were introduced throughout the development schedule, and as early as feasible.
- Multiple working groups (WGs) representing all team-elements, including the NASA HST Operations and Ground System Managers, were established. The function of these WGs were not only to flush out all requirements, testing strategies, failure scenarios, contingency plans, metrics identification and configuration management approaches, but to get "All-In" ownership of the process and product by the entire team. Work groups included:
  - Automated commanding procedures
  - State of Health monitoring of spacecraft telemetry
  - State of Health monitoring of ground network infrastructure
  - Situational awareness
  - Command Buffering
  - Alerting on-call staff
  - Automated Operations Roles and Responsibilities
  - Engineering workstation
  - Integration and Test.
- An AO Coordination WG was formed to facilitate communications and address issues between the WGs and to manage the progress of the overall AO schedule.
- In addition to a rigorous acceptance test and certification plan, a two-day mission simulation was conducted using HSTs Vehicle Electrical System Test Facility (VEST) high fidelity simulator suite. Multiple anomalies were introduced in both Observatory systems and ground systems/networks in order to exercise all on-call teams under both staffed and unstaffed situations, to observe anomaly coordination and responses, and to measure the response times. This highly successful simulation validated the AO concept, system design, operations procedures, and training.



**Figure 3. AO Delivery Chronology – Mitigated risk by deploying challenging aspects within initial releases and allowing for FOT shadow period**

#### IV. Hubble Automation Challenges and Solutions

The success of HST automated operations was contingent upon addressing the various challenges identified. Consequently, numerous changes were required both within the space and ground segments.

##### A. Automated Reporting System (ARS)

The first AO delivery was the Automated Reporting System (ARS) Release 1.0. HST high public visibility and designation as a “National Asset” dictated stringent reporting requirements. ARS 1.0 provided autonomous daily report generation and FOT log compilation based primarily on HSTARs, Control Center System (CCS) events, Ops Requests, Ops Notes, and flash reports, reducing the FOT workload to compile these reports (see Figure 4). The ARS 2.0 enhancement subsequently provided failover capabilities, a means to ingest inputs from additional sources, and an interface for providing engineering information to the STScI.



HST Report Date

- March 30, 2012
- March 29, 2012
- March 28, 2012
- March 27, 2012
- March 26, 2012
- March 25, 2012
- March 24, 2012
- March 23, 2012
- March 22, 2012
- March 21, 2012
- March 20, 2012
- March 19, 2012
- March 18, 2012
- March 17, 2012
- March 16, 2012
- March 15, 2012
- March 14, 2012
- March 13, 2012
- March 12, 2012
- March 11, 2012
- March 10, 2012
- March 9, 2012
- March 8, 2012
- March 7, 2012

HOME INTERNAL REPORT PUBLIC DRAFT ADMINISTRATION POT LOG

## Welcome to The Hubble Space Telescope Auto Report System

**HST Internal Report**  
Date: March 30, 2012  
99/0000z to 89/2359z

**HSTARS:**  
none

FGS ACO STATUS:	Scheduled	Successful	Unknown Failure Times
FGS GSACq	10	10	0
FGS REAcq	5	5	0
OBAD with Maneuver	7	7	0
LOSS of LOCK			

**CDSs:**  
none

**Commanding History:**  
 F-String 089/0153z ACE - ITCONN\_SC=1 ITTGT\_SC=HST  
 F-String 089/0153z ACE - INITPASS  
 F-String 089/0153z ACE - ACQUIRE  
 F-String 089/0155z ACE - ACQUIREFWD  
 F-String 089/0157z ACE - SSRDUMP 3 SCI 428  
 F-String 089/0201z ACE - LOADNSSCIBUF B21N31J0E Opportunity 1 of 19  
 F-String 089/0202z ACE - SSRDUMP 1 SCI 11619  
 F-String 089/0202z ACE - PASSEND

**486 ESB LIMIT UPDATES(ROP DF-18A):**  
none

**OPEN OPS REOs:**  
 17543-3 - Dump OBAD tables after failed OBAD  
 17659-4 - ESTR Reconditioning

**CONTINGENCY OPS REOs:**  
 18543-0 - CONTINGENCY: Controlled warm-up of WFC3 UVIS TECs  
 18736-0 - CONTINGENCY: Turn off WFC3 UVIS TECs after ramping  
 18851-0 - CONTINGENCY: FGS stuck in Coarse Track  
 19152-1 - CONTINGENCY GYRO RESTART

**COMPLETED OPS REOs:**  
none

**OPS NOTES EXECUTED:**  
none

**PASS OPS:**  
none

**TDRS CHANGES:**  
 2468 174 - West Event @089/1721z; Higher priority CRITICAL request  
 2469 174 - West Event @089/1903z; Higher Priority

**DAILY SUMMARY:**

Man. SCI SSR DUMP - 0	CDS - 0	LOR - 0
Man. ENG SSR DUMP - 0	HLGBU - 0	COP - 0
ETR DUMP - 0	Man. NSSC1 Direct LOAD - 0	R/T OBAD - 0
486 MEM DUMP - 0	Man. NSSC1 QBF LOAD - 0	NSSC1 DUMP - 0
486 SPC DUMP - 0	Man. 486 LOAD - 0	OPS REQ OPEN - 6
486 ESB DUMP - 0	EPHM LOAD - 0	OPS REQ COMPLETED - 0
HSTAR - 2	GENSLEW REQ - 0	OPS NOTES EXECUTED - 0
MODE 1 & MODE 2 - 0	DF-18A LIMIT - 0	ROP - 0

**ACE Initiated:**

Auto. SCI SSR DUMP - 16	ACE. Pass Init - 18	Auto. NSSC1 Direct LOAD - 0
Auto. ENG SSR DUMP - 1	ACE. Pass End - 18	Auto. NSSC1 QBF LOAD - 3
Auto. Tlm Acquire - 18	Auto. 486 LOAD - 1	Comm Loss - 0
Auto. Fwd Acquire - 18		

**STIS, NICMOS and SSR EDAC Error Log Histories:**  
none

**Flash Reports:**  
none

**COMMENTS:**  
none

Figure 4. Automated Reporting System Displays – Dynamically created and updated, remotely accessible report page provides status information and replaced daily manual generated reports

## **B. Coherent Mode**

Track and range data are required for orbit determination and are ultimately used to produce HST definitive and predictive ephemerides. As mentioned previously, track and range data collection were managed by the FOT ~8 times per day via spacecraft commands and GCMRs. To eliminate this manual intervention during unstaffed operations, the prime Multiple Access Transponder (MAT) was configured to full time coherent mode. This allowed track and range data to be collected any time the prime MAT was in use, without having to issue spacecraft commands and GCMRs. To maintain this configuration, PASS enhancements were implemented to activate the command carrier 30 seconds in advance of the associated return carrier. One penalty associated with coherent mode supports prohibited having a return carrier without a forward; a penalty that was deemed relatively insignificant in consideration of the eliminated commanding. Conversely, the ~30 seconds of real-time telemetry loss experienced during commanded transitions into and out of coherent mode were eliminated.

## **C. Co-locate Observatory Controllers, DOC, and PACOR Teams**

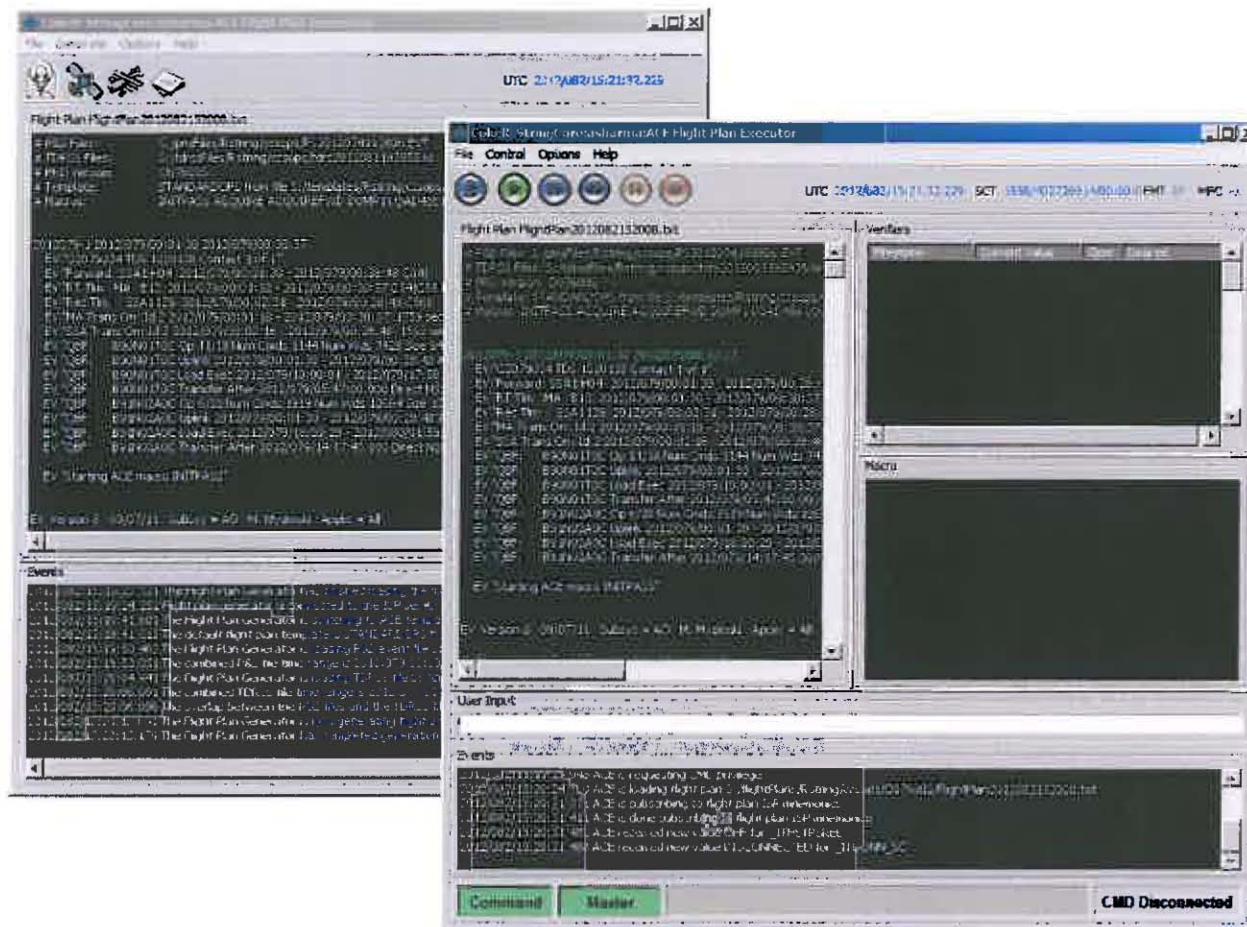
To resolve Operations team stratification issues, in November 2010 the Observatory Controllers, DOC, and PACOR teams transitioned from a segregated team/facility structure into a co-located unified team structure, and team members were identified as Mission Engineers (MEs). Operational procedure and training documentation and the system used to manage and track training and proficiency data were expanded to encompass the full set of operations performed by the unified team. Staff cross-training was completed to the levels specified in the AO training plan with each team member meeting AO training/proficiency requirements. MEs were involved throughout the entire development cycle to ensure they shared ownership. ME responsibilities were expanded to include the development and testing of new AO command procedures.

## **D. Automated Command Engine (ACE)**

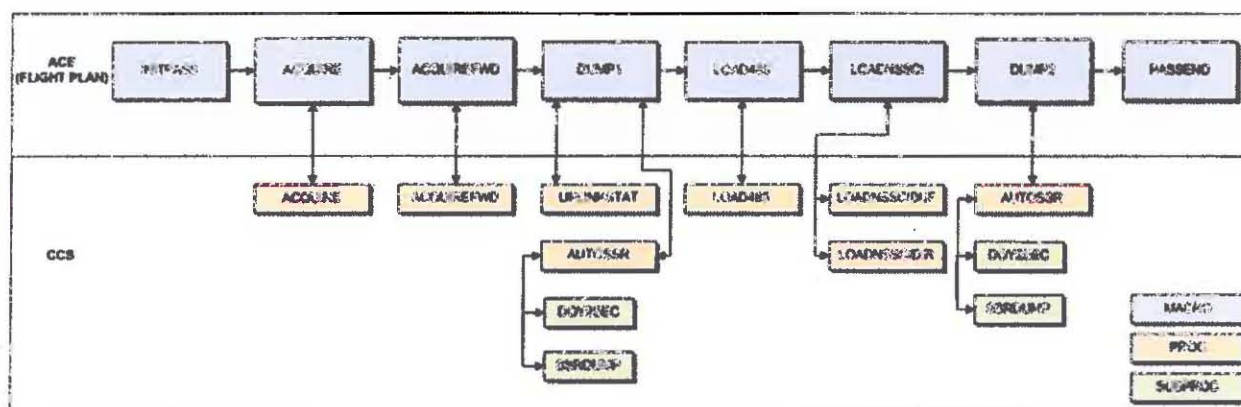
The Automated Command Engine (ACE) conceptually serves as an auto-pilot and performs all commanding during unstaffed periods. The ACE executes a pre-defined command execution and telemetry collection schedule (a.k.a., Flight Plan). The ACE confirms that TDRSS contacts occur as scheduled and acts to establish or restore TDRSS contacts when they deviate from the schedule. Upon confirming the scheduled contact has activated, the ACE performs stored command loads and SSR dumps according to the scheduled time remaining in the contact. The ACE produces the Flight Plan upon user request or autonomously upon detecting revised schedule data through the Space Network Access System (SNAS) client interface (see Figure 5).

The ACE utilizes a standard template that defines the list of major activities to be performed in sequence for every TDRSS contact. Each major activity is defined by a macro containing the logic that ultimately specifies Command Control Language (CCL) procedures (a.k.a., CCLs) and associated variables to be executed on the legacy CCS (see Figure 6). The ACE autonomously issues responses to prompts that would otherwise be issued to the FOT during staffed operations. When commanding anomalies or significant TDRSS contact anomalies are detected, the ACE and its macros and CCLs all issue alerts to the Alert system. The use of templates, macros, and CCLs within the overall ACE architecture provides the ability to quickly respond to changing spacecraft conditions.





**Figure 5. ACE Flight Plan Generator and Executor Displays** – Flight Plan Executor display (right) allows operators to see the currently executing flight plan and status, and allows them to halt the plan and immediately take manual control



**Figure 6. Flight Plan Contact Processing Flow** – Expansion of Templates, Macros and execution by CCLs allow flexibility for flight plan changes without changing the generation software itself

#### E. SNAS Interface for Automating TDRS Schedule Updates

As a user of the Space Network, HST is subject to changes in the TDRS schedule. Although TDRS schedule changes can occur at any time, most schedule changes occur at least several hours prior to the affected scheduled

contact. HST staff coordinated with the SNAS Development Project to implement SNAS client interface enhancements that ultimately trigger autonomous Flight Plan generation upon detecting TDRSS schedule changes. A governing Interim Support Instruction (ISI) with WSC defines the methods by which WSC staff may initiate contact with the FOT when Space Network driven schedule changes are required. The SNAS client interface itself allows the FOT to perform TDRSS schedule changes remotely during unstaffed periods, eliminating the need for the FOT to report to the Control Center to enact trims to scheduled contacts or even to delete contacts. Contact extension and added contacts may also be remotely scheduled; however, the FOT must be present in the Control Center when those contacts are active as automated commanding does not alter the on/off state of HST's transmitters and thus no automated commanding will occur within those periods. When TDRS schedule changes are subsequently detected by the HST ground system, a new Flight Plan is autonomously generated 10 minutes prior to the next scheduled contact. In the unlikely event that a schedule change is received within the 10 minute window of its associated service activating, the ACE manages execution of the contact to ensure that commanding is performed only while the service is active.

#### **F. Alert System**

With the advent of unstaffed operations, systems needed to be deployed to autonomously detect numerous types of spacecraft and ground segment anomalies and to autonomously alert the appropriate on-call personnel to ensure a timely response. An Alert System was deployed that accepts anomaly information from the space or ground segment components and issues escalating and/or informational alerts to specified on-call groups. The Alert system autonomously escalates alerts through on-call groups according to pre-defined schedules until acknowledgements are received. Alerts can be sent via Short Message Service (SMS) and via email to users or groups of users, and can be acknowledged in the same manner or via a secure web interface. To address concerns regarding potential alert flooding events, an enhancement was deployed that bins alerts according to configurable criteria on a user group basis. Weekly paging tests were initiated in October 2010 to ensure that all on-call personnel were trained in the response procedure well in advance of the first unstaffed periods. The alert system is fully redundant and supports multiple delivery methods in the event of a transmission failure. Smart phones (iPhones) on two different major service networks were distributed to on-call staff to mitigate potential risks associated with service network outages. To facilitate the process of performing off-hours TDRSS schedule changes, the Alert system also features an interface that allows WSC staff to initiate contact with the FOT during unstaffed periods by accepting WSC emails and transforming them into an SMS sent to on-call FOT staff.

#### **G. Spacecraft Health and Safety Monitoring**

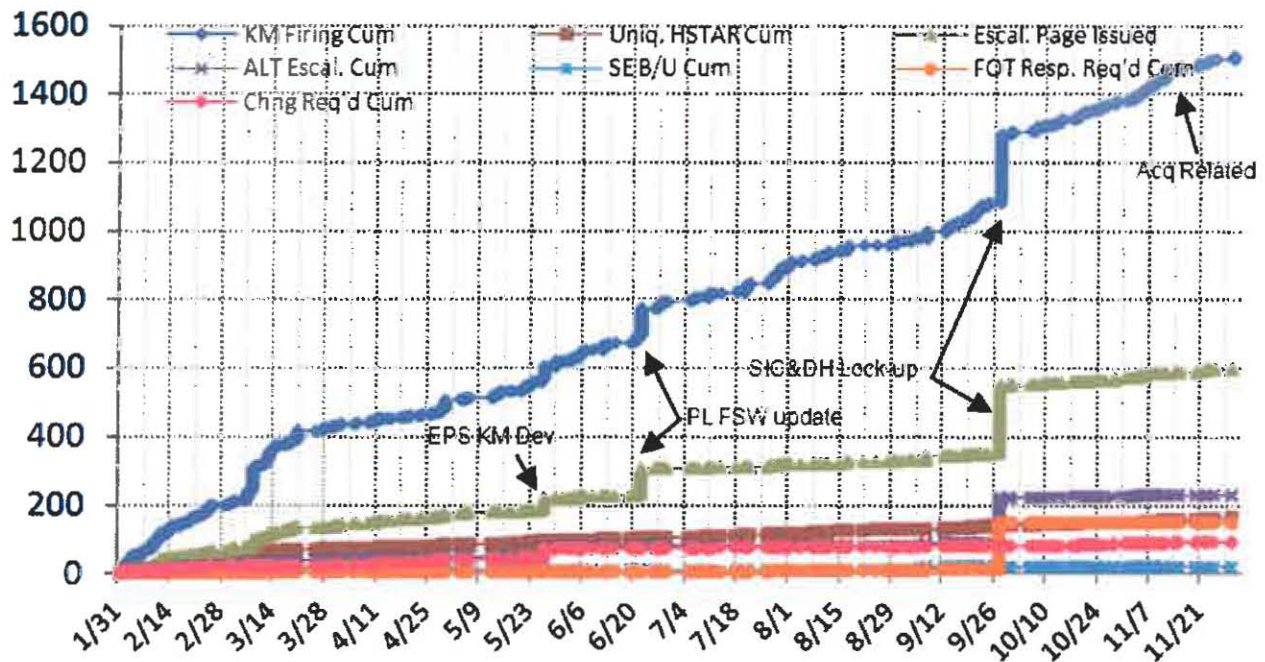
Both on-board and ground limits thresholds were previously optimized for 24x7 staffed operations. Unstaffed operations demanded extensive enhancements to spacecraft health and safety (H&S) monitoring capabilities. Visual alerts that were previously conveyed to the on-duty FOT now needed to be actively distributed directly to the appropriate on-call staff which does not necessarily include the on-call FOT. Consequently, the spacecraft engineers reviewed and modified limits associated with over 3900 telemetry mnemonics, and a Key Monitor System was deployed that automated spacecraft telemetry limits violation assessments and corresponding actions. System Generated Key Monitors (SGKMs) were initially defined that applied spacecraft engineer-specified persistence thresholds, messages, and actions for each yellow and red limit violation for each mnemonic. To accommodate more complex logic typically associated with ROOL violations, User Generated Key Monitor (UGKM) functionality was deployed allowing the spacecraft engineers to specify complex logic, to correlate values for multiple mnemonics, and to specify value limits that override yellow and red limits thresholds.

The Key Monitor System also allows spacecraft engineers to define UGKMs in real time in response to changing spacecraft conditions, and provides for configuration management of all Key Monitors. Key Monitors issue alerts and events; however, they're also capable of generating pre-defined reports and plots (see Figure 7). Tracking of Key Monitor firing metrics in 2011 (Figure 8) was essential in refining configuration parameters and in assessing whether the associated alert levels were sustainable.



**Figure 7. Key Monitor Tool Displays** – Suite of tools enables rapid creation, verification, monitoring and configuration control of Key Monitors





**Figure 8. 2011 Key Monitor Firing Metrics** – Trend of cumulative Key Monitor firings, escalating alerts issued, escalating alerts not responded to by primary on-call engineers, and firings that resulted in Key Monitor changes and FOT response required

#### H. Ground System Health and Safety Monitoring

The HST Ground System remains fully redundant, supporting both string and facility failover/isolation. No single points of failure exist within the ground system allowing contact with HST to be maintained throughout scheduled contacts. Multiple tools (see Figure 9) provide visual alerts to operators in the event of ground system component failures. To accommodate unstaffed periods, ground system H&S monitoring enhancements autonomously detect anomalies and alert the appropriate on-call staff.

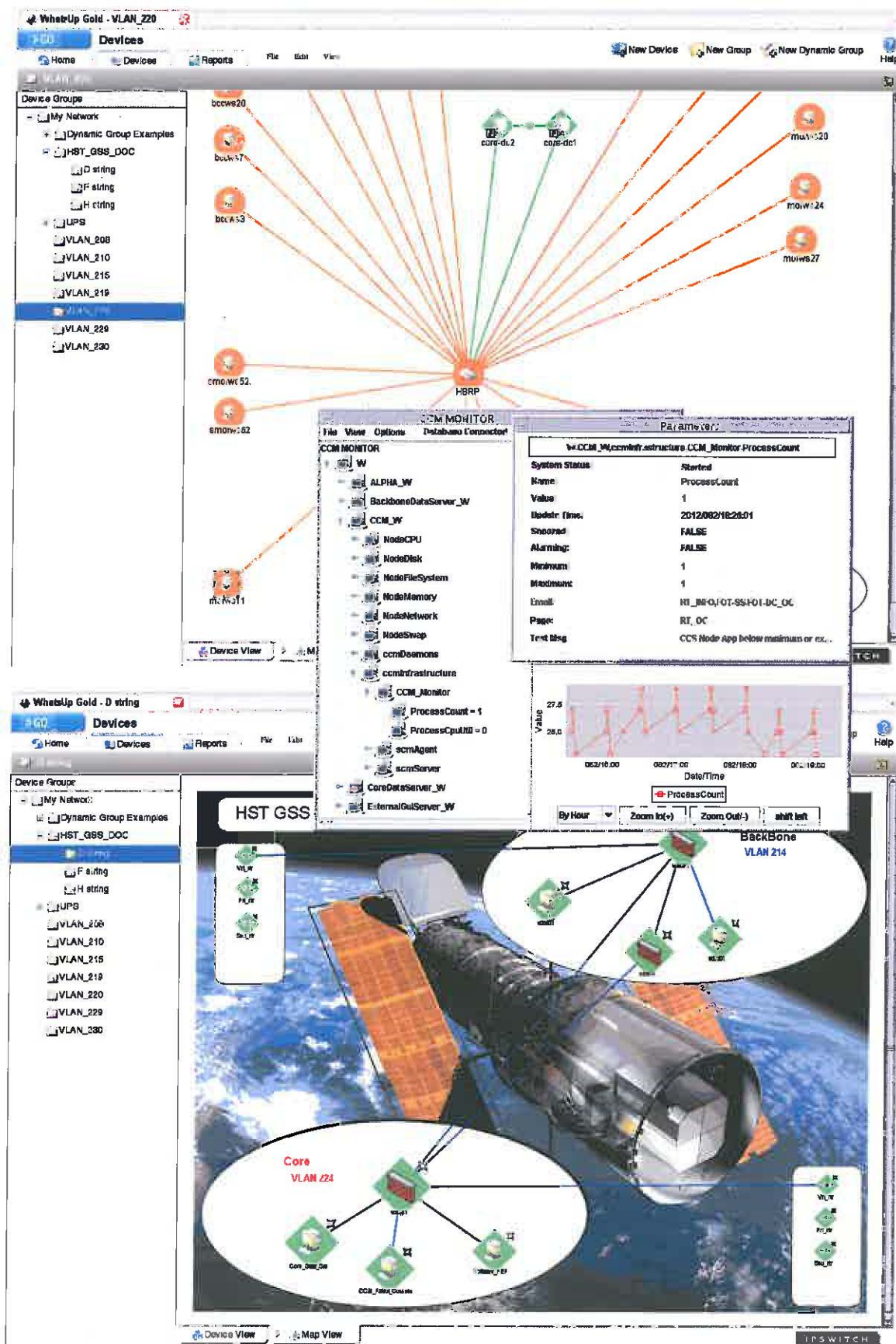


Figure 9. Ground System Monitoring Displays – Multiple tools monitor the status of critical ground system elements

#### **I. Buffered Payload Stored Command Load (QBF)**

The bus computer was designed with a much larger memory than the payload computer. Flight Software (FSW) staff conceived of a means of buffering payload stored command loads in the bus computer and then transferring them at the appropriate time to the payload computer. The FSW within the bus and payload computers, PASS, and CCS were all extensively modified to generate, uplink, and ultimately transfer to the payload computer the new type of buffered payload stored command load. This effectively increased the load windows for payload stored command loads from ~3½ hours to ~24 hours. FSW staff also extended the bus computer stored command load windows from ~4 to ~12 hours. CCS was modified to mark payload stored command loads or their associated QBF loads as having been uplinked when a sibling is uplinked, to provide the Situational Awareness System (SAS) with the current list of loads that are within their load windows that await uplink, and to issue an alert when a given QBF or bus stored command load has not been uplinked and is within 5½ hours of the end of its load window. In so doing, the FOT was provided a large window of opportunity to report to the Control Center during unstaffed periods to manually uplink stored command loads in response to automated commanding problems.

During the implementation of the QBF capability, FSW staff identified the potential for command collisions between ground commands and commands originating on the spacecraft. In order to mitigate risks imposed by potential command collisions, PASS was modified to advance the start of the transfer windows into the several minute period immediately preceding TDRS contacts, allowing transfers to be completed prior to the contact being established. In so doing, the potential for command collisions between ground commands and on-board commands involved with the transfer of QBF loads to the payload computer was nearly eliminated. Procedures used for manual commanding of the payload were also modified to temporarily disable the transfer function thereby eliminating remaining command collision concerns.

Note: As an additional benefit, the effective increase in the load windows for payload and bus computer stored command loads to ~24 hours and ~12 hours, respectively allowed additional reductions in MAT cycling to be realized. Essentially, the need to have specific TDRS contacts dedicated only to uplinking a stored command load was significantly relaxed.

#### **J. Guide Star Acquisition Monitoring**

Guide Star Acquisition (GSAcq) monitoring is of special interest to the FOT and SE disciplines; so much so that GSAcq metrics are included within daily reports. GSAcq failures preclude the collection of science data by the various science instruments, and multiple consecutive GSAcq failures will eventually result in on-board attitude determination problems that require manual intervention to resolve.

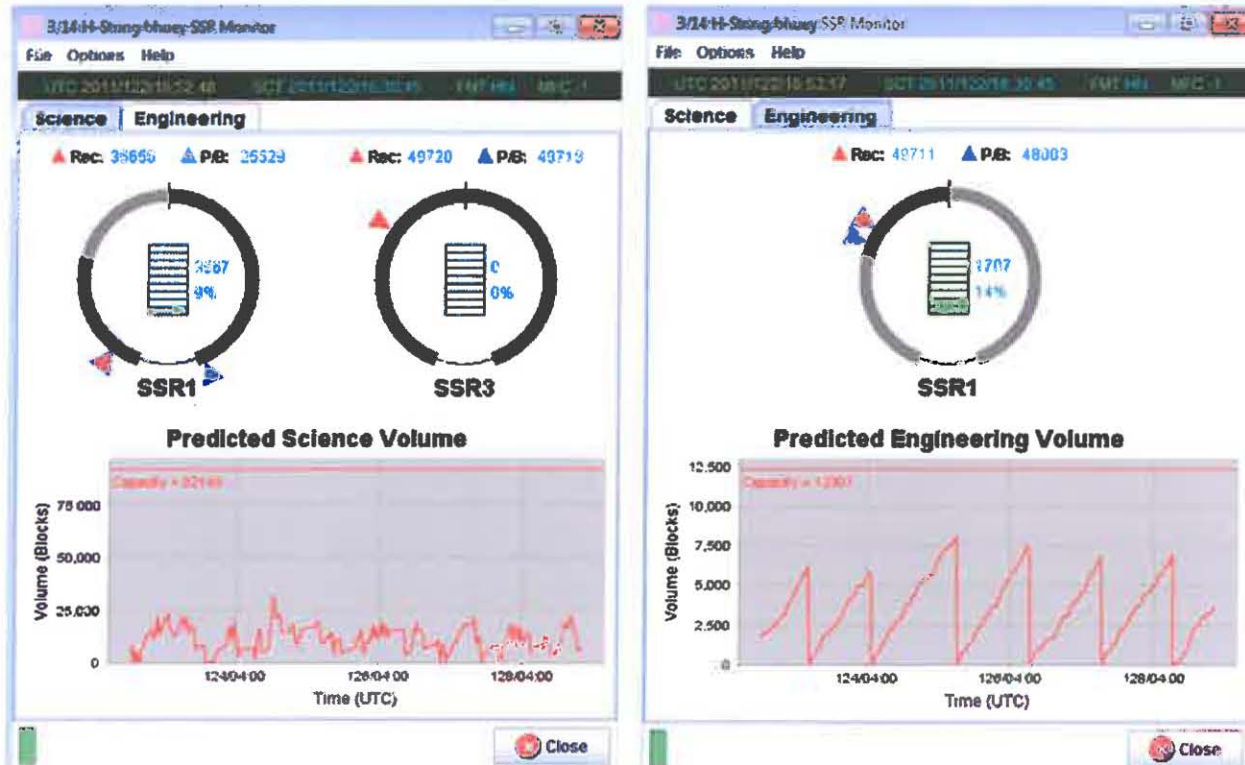
To eliminate the need for the FOT to continuously monitor GSAcq status, FSW changes were deployed to count and report in telemetry the number of consecutive GSAcq failures. This telemetry was then Key-Monitored to autonomously alert on-call staff when persistent GSAcq failures are encountered. Lastly, a tool was deployed to the Engineering Workstations to perform long term GSAcq trending and to provide GSAcq metrics to ARS for inclusion within daily reports.

#### **K. Solid State Recorders Monitor**

During 24x7 staffed operations, the FOT monitored the state of the SSRs and, if necessary, would schedule additional TDRS contacts to dump the SSRs to avoid data loss. As one mitigation against the risk of potential data loss during AO, the SSR Monitor tool was deployed that tracks the current states of the SSRs and dynamically predicts potential data loss through the end of the most recently received set of stored command loads (i.e., typically 4 to 11 days in the future) based on the current SSR data volumes, the current TDRS schedule, and the science observation schedule.

The SSR Monitor (see Figure 10) tool issues cautionary event messages if any data loss is predicted within the next four days, and it issues both critical event messages and alerts when science or engineering data loss is predicted within more imminent 12 or 24 hours windows, respectively. The SSR Monitor tool also provides the current states of the SSRs to SAS.





**Figure 10. SSR Monitor Tool Displays** – Current and predicted data volume on the recorders based on real-time telemetry, latest TDRS schedule, and estimated observatory data collection is displayed

#### L. Situational Awareness System (SAS)

During 24x7 staffed operations, the FOT maintained continuous situational awareness that was facilitated largely via shift handovers. With the first unstaffed periods, the FOT would no longer conduct shift handovers, nor would they even be the first responders for various types of anomalies. SAS was deployed to provide a quick means of remotely assessing the basic status of the spacecraft and the ground system, and to track anomaly response information. SAS was designed to provide simple web pages (see Figure 11) of basic spacecraft telemetry mnemonics, event data, SSR status information, stored command load uplink status information, Flight Plan information, a message board, and links to important additional information, all suitable for secure, remote display on desktop computers, laptops, and smart phones.



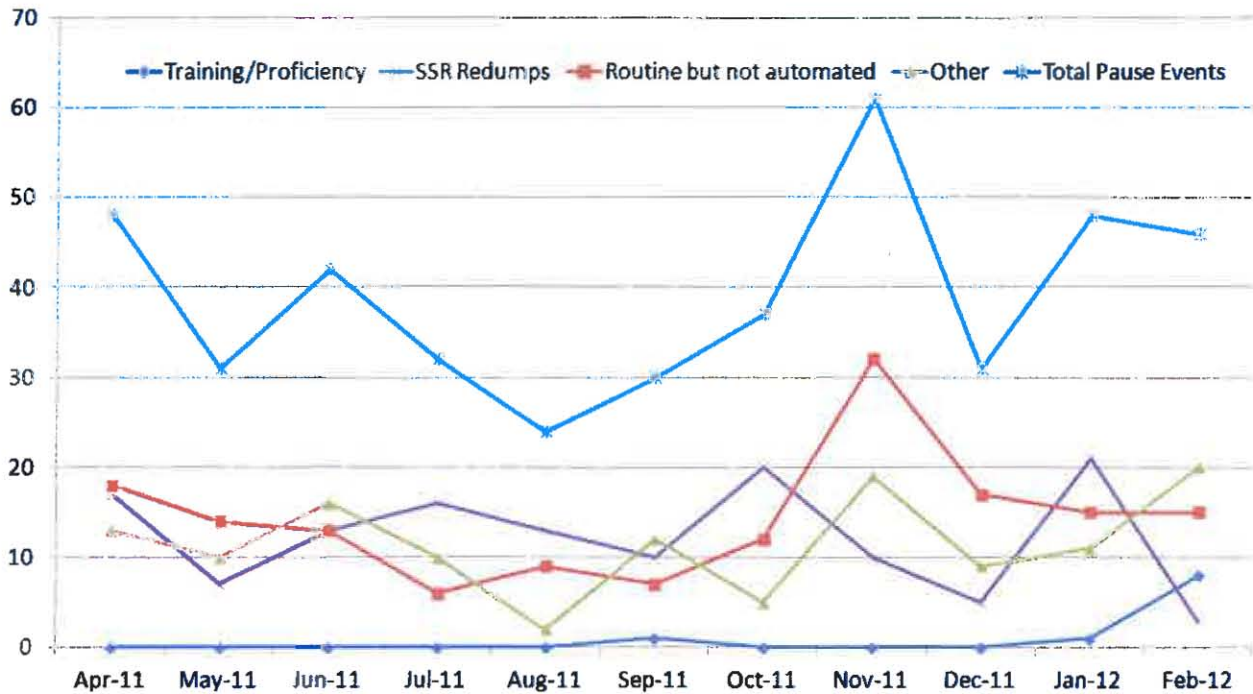
**Figure 11. Situational Awareness System Displays** – Remotely accessible status pages allow for knowledge and coordination of key operations status

#### **M. Science Data Packet Processor (a.k.a., PACOR)**

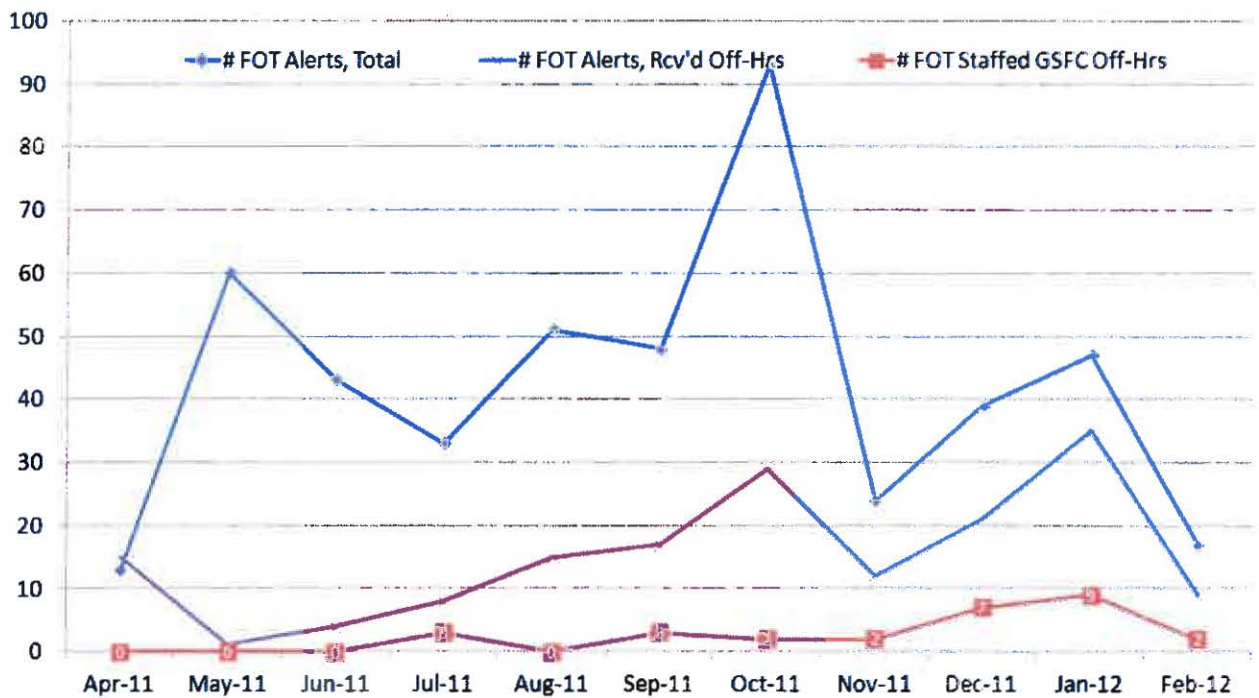
Prior to automation, science data loss monitoring and response was almost completely manual, relying on PACOR Analysts to identify science observations featuring padded or missing data, and to subsequently act to resolve the data anomalies in order to achieve the phenomenal ~100% science data return. Barring moderate levels







**Figure 13. Manual Commanding Metrics – Trend of how often the FOT takes manual control and why**



**Figure 14. Flight Operations Team On-Call responses – Trend of how often and when the FOT is paged, and required immediate response**

Freed from continuously manning the operations consoles, the FOT has expanded its roles and responsibilities and now supplements the Hubble Integrated Test Team (HITT) to support acceptance testing of software and

operations procedures, and verification of authorized ground system changes. The FOT has also expanded its role into areas previously done by Systems Engineers.

Systems Engineers are continuing a cross-training program in order to enhance their depth of knowledge on multiple HST subsystems (electrical, thermal, attitude control, safing, optical telescope assembly, communication and data management) in order to increase the depth of each team as a means to mitigate staff attrition risk.

It is important to note that since going operational with AO the data loss is only around 0.1%. This percentage is figured as the percentage of observations missing any bit and therefore potentially impacted. The majority of the time the loss even within those .1% missing bits is insignificant to the science objective.

Part of the culture change was just letting folks understand that Management had agreed to a change in expectations. For instance, many in the FOT felt they were expected to always be aware of the current status of on-orbit events (roles & responsibilities). They felt the need to sit on console when they were at work and watch the automation. GSFC and MOSES management had to explicitly tell them to sit in their offices where they could be more productive on other tasks and that they would not be expected to be fully aware of the current spacecraft events to a fine detail. While this was a tough culture change, the FOT were successful in making it and are now available to be fully engaged in other tasks in support of Operations.

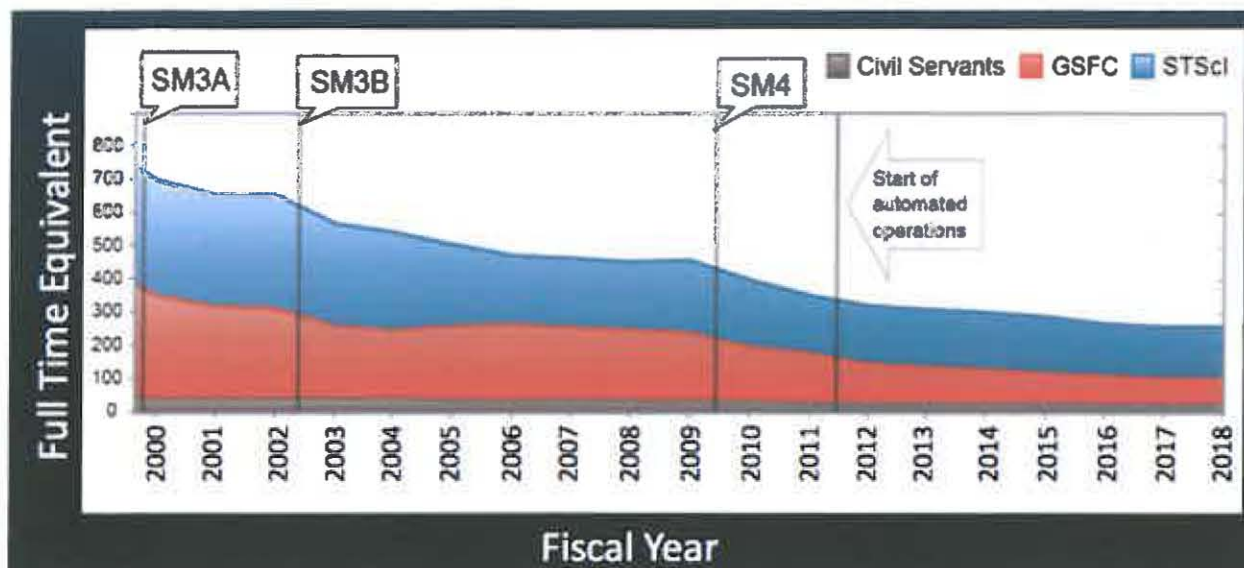
The flexibility of the automation systems has been tested this past year by Observatory anomalies including the failure of the prime transponder to operate in coherent mode, and by lock-ups of the Solid State Recorders. In these cases, and others, modifications to the macros and CCLs run by the ACE, and the modification of Key Monitors or the generation of new Key Monitors to detect recurrence of the anomaly have been rapidly deployed.

The Key Monitors (KM) that check the health and safety of the observatory continue to be adjusted, although the rate of change has significantly settled. While some changes have been made due to the continuing evolution of the Observatory and flight software modifications, or to reduce the frequency of nuisance alarms, most changes have been adding email notification to all members of a given team, instead of just an escalating alert to the team on-call member.

Alerts relating to the state of the ground system and network constitute approximately 75% of all alerts that have been generated, while observatory KMs account for the remaining 25%. Of the ground system and network alerts, the majority of these are due to planned maintenance activities such as security scans, patches and reboots. Issues related to over-paging were carried as a risk item during the development of the automation, but one year of operations experience has proven that the paging rate is sustainable indefinitely.

Improvements to the ground system and automation capabilities continue to be introduced. Among the most significant enhancements are:

- Automation of science data re-dumps when data is corrupted by RFI during downlink. When the level-0 processing system detects such data losses, its re-dump reports are now routed back into the automation system where enhanced CCLs execute the re-dump, or not depending on the current volume of stored data in the Solid State Recorders.
- The Automated Control Engine (ACE) and CCLs now handle cases where there are multiple forward links in any given pass. Although this is rare, normally occurring only a few times a year, manual intervention by the FOT is no longer required.
- The ACE also now verifies that sufficient uplink opportunities exist for all loads when it generates a flight plan. This provides additional protection against too few uplink opportunities should TDRS schedule changes limit the number of forward links.
- The Key Monitor system now has a configurable settling time after minor frame gaps, which makes false alerts less likely, and now includes a 'solve-from-file' capability to facilitate the testing of new or changed Key Monitors.
- Multiple alerts are now combined to prevent an 'alert-flood' condition. Significant spacecraft anomalies such as an entry into safe-mode can generate over 100 escalating alerts. Previously the TelAlert system manager would have to manually intervene to clear the system and halt the escalations. Now, the system automatically detects an alert flooding condition and subsequently collects the multiple alerts and sends a single escalating alert with a link to a dynamically created webpage listing all the individual alerts.



**Figure 15. HST Operations Staffing – Trend and plan of HST operations staffing**

The Hubble Space Telescope remains in excellent health following Servicing Mission 4 in May 2009. HST scientific output is higher than ever and is increasing, its observation time continues to be heavily oversubscribed, demand for archival data is increasing, and citations to HST publications are increasing exponentially. With the cost of mission operations at the lowest it has ever been (see Figure 15), HST is well positioned for another decade of amazing discoveries.

## Appendix A Acronym List

<b>ACE</b>	Automated Command Engine
<b>AO</b>	Automated Operations
<b>ARS</b>	Automated Reporting System
<b>CCL</b>	Command Control Language
<b>CCS</b>	Control Center System
<b>DOC</b>	Data Operations Center
<b>EWS</b>	Engineering Workstation
<b>FOT</b>	Flight Operations Team
<b>FP</b>	Flight Plan
<b>FSW</b>	Flight Software
<b>GCMR</b>	Ground Control Message Request
<b>GSFC</b>	Goddard Space Flight Center
<b>H&amp;S</b>	Health and Safety
<b>HST</b>	Hubble Space Telescope
<b>HSTAR</b>	Hubble Space Telescope Anomaly Report
<b>ISI</b>	Interim Support Instruction
<b>KM</b>	Key Monitor
<b>LOS</b>	loss of signal



<b>MAT</b>	Multiple Access Transponder
<b>ME</b>	Mission Engineer
<b>NSSC-1</b>	NASA Standard Spacecraft Computer Model 1
<b>OOL</b>	Out of Limit
<b>OST</b>	Operations Support Team
<b>PACOR</b>	Science Data Packet Processor
<b>PASS</b>	Planning and Scheduling
<b>QBF</b>	Buffered Payload Stored Command Load
<b>ROOL</b>	Routine out of Limit
<b>SAS</b>	Situational Awareness System
<b>SCM</b>	System Configuration Monitor
<b>SGKM</b>	System Generated Key Monitor
<b>SMS</b>	Short Message Service
<b>SN</b>	Space Network
<b>SNAS</b>	Space Network Access System
<b>SSA</b>	South Atlantic Anomaly
<b>SSA-R</b>	S-Band Single Access Return
<b>SSR</b>	Solid State Recorder
<b>STOCC</b>	Space Telescope Operations Control Center
<b>STScI</b>	Space Telescope Science Institute
<b>TDRSS</b>	Tracking and Data Relay Satellite System
<b>UGKM</b>	User Generated Key Monitor
<b>VEST</b>	Vehicle Electrical System Test
<b>WG</b>	Working Group
<b>WSC</b>	White Sands Complex

### **Acknowledgments**

The authors wish to acknowledge and thank all members of the HST Team. This effort required end-to-end changes to HST Operations and required leadership and support from Project Managers, Flight Operators, Planning System and Ground System Developers, Flight Software Engineers, Hubble Integrate Test Team Engineers, Systems Management, Systems Engineers and System Administrators.

### **References**

Prior M., Wright N., “Operations Modeling for the Hubble Space Telescope Mission”, RCGSO, SP-648, Moscow, 2007